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A NEW RADIOGRAPHIC CORROSION INSPECTION CAPABILITY

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13 December 1988

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Corrosion of equipment and material costs the Armed Forces billions of dollars each year. A need currently exists for a cost-effective nondestructive inspection tool able to detect corrosion within military equipment. Dual-Energy Radiography was proposed as a potential NDE corrosion inspection method. A program was undertaken to construct a preprototype dual-energy scan system. An effective dual-energy detector system was designed and fabricated, dual-energy software was coded, and a complete dual-energy system also capable of laminography was constructed. The results of this program are a fully operational preprototype Dual-Energy/Laminography system.

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SUMMARY

Corrosion of equipment and material is a widespread problem. For the Armed Forces, preventing, detecting and repairing corrosion is a crucial part of their continuous struggle to keep military systems in full combat readiness. A recent study by the National Bureau of Standards titled "Economic Effects of Metallic Corrosion in the United States," estimates corrosion-related problems cost the U.S economy over $70 billion annually. A similar figure has not been placed on corrosion losses within the Armed Forces, but it is certainly in the billions of dollars [1]. In October 1980, the Joint Logistics Commander established a Joint Panel on Corrosion Prevention and Control with one of its specific objectives being to provide special emphasis on the development of new corrosion-sensitive NDI techniques with the potential to provide rapid, large-area inspections. Concurrently, a Joint Technical Coordinating Group on NDI was also established to develop an effective corrosion inspection technique as one of their high priority tasks. As a result of these efforts, a major workshop on the NDE of aircraft corrosion was held at Wright Aeronautical Laboratories, Dayton, Ohio, in May 1983. The Phase I proposal of a new radiographic corrosion inspection technique utilizing dual-energy radiographic principles was a direct response to the proceedings of that workshop.

The results of a 24-month Small Business Innovative Research (SBIR) Phase II program (Contract F33615-85-C-5151) dealing with dual-energy radiography are documented. The program was divided into four tasks which are as follows: (1) design and fabrication of a detector system, (2) design and coding of appropriate software, (3) system integration and evaluation, and (4) a demonstration of the capabilities of the instrument to a select government/industry audience.

The product of this Phase II SBIR program is a fully operational preprototype LAMinography/Dual-Energy system designated the **LAM/DE** System. The scope of the program was reduced because a detailed evaluation of dual-energy capabilities and limitations and a government/industry demonstration could not be performed within established program funding limits.

FOREWORD

This final report was prepared by Advanced Research and Applications Corporation (ARACOR), Sunnyvale, CA, and documents the work performed under Air Force Contract No. F33615-85-C-5151, "A New Radiographic Corrosion Inspection Capability."

The work was conducted under the cognizance of the Materials Laboratory, Air Force Wright Aeronautical Laboratories, Air Force Systems Command, Wright-Patterson Air Force Base, Ohio 45433-6533. Capt. Michael Polovino, AFWAL/MLLP, was the Air Force Program Manager for the initial part of the program and Dr. Tom Moran was the Air Force Program Manager for the later part of the program. The ARACOR Program Manager was Dr. James H. Stanley.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

SECTION 1

INTRODUCTION

The problem of detecting and estimating the extent and severity of hidden corrosion in aircraft structures has been a major concern to the USAF NDE community for a number of years. In the past, attempts to elicit solutions to this expensive problem via workshops and requests for proposals for potential solutions have produced very little substantial progress. The successful demonstration of the feasibility of dual-energy (DE) radiography shown in the Phase I program represents a significant advancement.

Detection of corrosion in real structures is complicated by the myriad of geometric configurations encountered in actual objects as well as because a significant amount of corrosion is either not immediately accessible to the inspector or is invisible to commonly used inspection techniques. Consequently, new inspection procedures and/or technologies which are more quantitative, more reliable, more reproducible, more rapid, more economical, and more forgiving than current methods are needed. Real-time radiography has been identified as one of several technologies that significantly promises to provide improved corrosion detection [1-4]. Real-time systems have the potential to provide rapid, semi-quantitative inspection; and if the data are converted to digital format at some stage in the signal processing chain, various spatial- and temporal-mask subtraction techniques and a variety of enhancement routines could conceivably be used to provide an automatic corrosion detection and assessment capability. Yet, in spite of the potential advantages allegedly possessed by real-time systems, they have not to date demonstrated a significantly better ability to detect corrosion in its early stages (when corrective actions can most efficiently be taken) than other competing modalities [5].

In January 1984, in response to an SBIR solicitation, ARACOR proposed to the Air Force a new radiographic inspection technique based on dual-energy principles. ARACOR had been exploring dual-energy methods, particularly as applied to Computed Tomography, for half a decade; but to the best of our knowledge, this was the first time dual-energy radiography had been proposed for an industrial application. Exploring the efficacy and sensitivity of dual-energy digital radiography in detecting early indications of corrosion was the main goal of the proposed effort.

Based on the Phase I results, the dual-energy technique offers a powerful means of dealing with a large subset of corrosion detection problems. Foremost, it should significantly enhance or augment the corrosion detection and damage assessment capabilities of any real-time system. Furthermore, the improved sensitivity offered by dual-energy methods can be traded for an equivalent detectability at a much reduced dose level, an important consideration in close environments, such as on-board or *in situ* inspections. In those areas where real-time radiography has already been demonstrated, or is expected to demonstrate, an ability to produce useful inspections, the proposed technique will serve to improve the examination and to expand the range of valid applications. In those areas where real-time radiography is at best marginal, dual-energy processing may make some otherwise impractical applications feasible. Either way, wherever real-time radiography finds an application in corrosion detection and prevention, dual-energy radiography will offer substantial improvements in detection sensitivity and damage assessment.

SECTION 2

TECHNICAL BACKGROUND

The term "dual-energy" is utilized in this context to indicate that as a standard part of the inspection procedure, radiographs are taken at two different effective energies and implicitly assumes that the radiographs are digital at some point in the processing so that they may be analyzed to provide additional information not otherwise available with conventional (single-energy) radiographic systems. The approach relies on the fact that in the energy range from a few keV to many MeV, all but a small number of minor effects are explainable in terms of just three photon-matter interactions -- photoelectric, Compton, and pair production; and that at energies below about 1 MeV, the Compton effect and the photoelectric effect dominate, while above several MeV, the Compton effect and pair production dominate. Consequently, since no more than two interactions need to be considered at one time to account for the attenuation of X-rays in matter when dealing with the physics of radiography, digital radiographs obtained at two different energies can be analyzed to obtain the individual contributions of the competing interactions to the total attenuation. Further, because the photoelectric and pair production effects are sensitive to density, the effective atomic number and density of each point in a radiograph can be determined from views taken at two different energies. In other words, detailed material properties can be extracted from dual-energy radiographs.

This process is carried out by algebraically processing two radiographs taken at different X-ray tube energies to extract a pair of new images, one referred to as the "Compton image" and one referred to as the "photoelectric image." Since these in turn depend in known ways on the density and atomic number, they provide a powerful handle for determining the fundamental physical properties of the material under examination. A particularly powerful use of this technique is to "cancel the predominant material in the image to improve the conspicuity of other materials that may be present. This is accomplished by performing a weighted subtraction of the "Compton image" from the "photoelectric image," where the relative proportions being selected are such that the "Compton image" equals the "photoelectric image" or the material the user wishes to eliminate. Since the magnitude of the "Compton image" and the "photoelectric image" vary systematically over the elements, only one element (or compound) at a time can be

cancelled in this manner leaving a residual image for different elements and/or compounds.

The power of this technique allows the user to identify different materials in the object under examination. For instance, if an aircraft structure is composed largely of aluminum, then the aluminum could be cancelled and the residual image studied. Only non aluminum material would be present in the image. Normally expected items, such as fasteners, gaskets, sealants, etc., would be readily recognized by the inspector, and any corrosion or other foreign matter, if it exists, would be visible as anomalous patches of unexpected material. Since non aluminum items are generally well known and well specified; and since further, those areas most likely to corrode are presumably well-defined, then to search for the presence of corrosion in susceptible components should be straightforward. This technique might also offer a rapid way to screen for missing components, such as critical washers or gaskets, since the conspicuity of small parts is greatly increased when more dominant materials are cancelled in a radiograph.

SECTION 3

PROGRAM REVIEW

This Phase II SBIR program was divided into four separate technical tasks as follows: (1) design and fabrication of a detector system, (2) design and coding of appropriate software, (3) system hardware/software integration and evaluation, and (4) demonstrate the capabilities of the instrument to a select government-industry audience.

This program was linked to a companion program, "A New NDE Capability for Thin-Shelled Structures" (Contract F33615-85-C-5145). This program designed and fabricated the detector system, including the detectors and the data acquisition electronics, and developed and coded the appropriate software modules. The companion program was responsible for the "hardware" design, such as the detector collimators and housing, the handling system, and the radiation source. Procurement of all materials was handled by the other program. A discussion of the tasks completed as part of this program follow.

3.1 DETECTOR DESIGN

The major hardware design task required of this particular program was the design of the detector system. This includes the sensors themselves along with the associated data acquisition electronics. This task will be described below.

3.1.1 Sensor Design

To construct a dual-energy and a laminography system, we paid special attention to the detector system so that we could meet the measurement requirements for both capabilities could be met with a single design. The design variables considered were detector orientation, detector elements per channel, detector housing, number of detectors, etc. These design issues were resolved to provide the most cost-efficient detector system consistent with funding limitations that would support both programs.

It was decided to place the detector array in a modified ARACOR detector package to reduce design costs. The DE detector array was designed as discrete sensor elements to technologically reduce risk and contain costs. The initial design called for 6 elements per detector channel but after further study it was determined that 2 elements per channel would be sufficient. To fit within the budget outlines, the final design was limited to 64 dual in-line detector elements although, in principle, the detector housing could accommodate up to 160 detector channels. A schematic of the individual detector setup is shown in Figure 1.

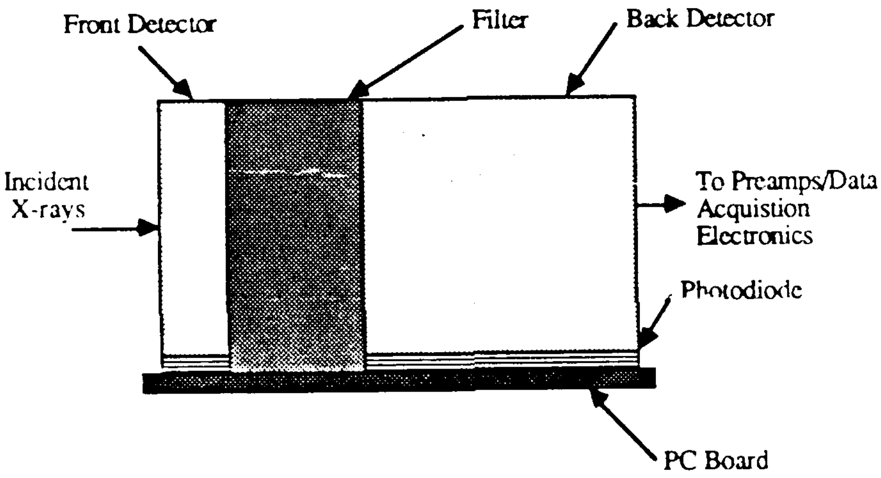

FIGURE 1: Individual Detector

3.1.2 Data Acquisition Design

A schematic of the data acquisition signal-processing path is shown in Figure 2. The X-rays are absorbed at the detector boards by scintillator crystals which produce a visual fluorescence in proportion to the amount of X-rays absorbed. This optical light is converted to an electrical signal which is in turn amplified and processed by the analog boards. This signal is then digitized at the ADC board and fed into the scan control computer via the array processor which processes the information. The processed data are then reconstructed and displayed by the imaging computer.

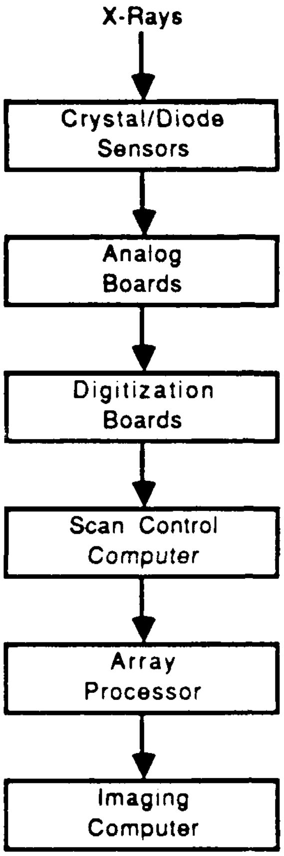

FIGURE 2: Data Acquisition Block Diagram

The analog and digitization boards were designed as part of the LAM/DE program, drawing on design experience with previous programs. Schematics of the layouts presented at the CDR for the analog processing boards are given in Figures 3 and 4. A CDR schematic of the layout for the digitization boards is given in Figure 5. A CDR layout of the cabling for the data acquisition system is given in Figure 6. A photograph of the data acquisition electronics is shown in Figure 7.

3.2 SOFTWARE DEVELOPMENT

A large portion of the software effort was expended on the dual-energy and laminography software development. Both methods required additional design and coding to adequately satisfy the LAM/DE requirements. Both program modules were incorporated into ARACOR's existing CATS© software package. Software also had to be developed to execute the necessary control of the LAM/DE system.

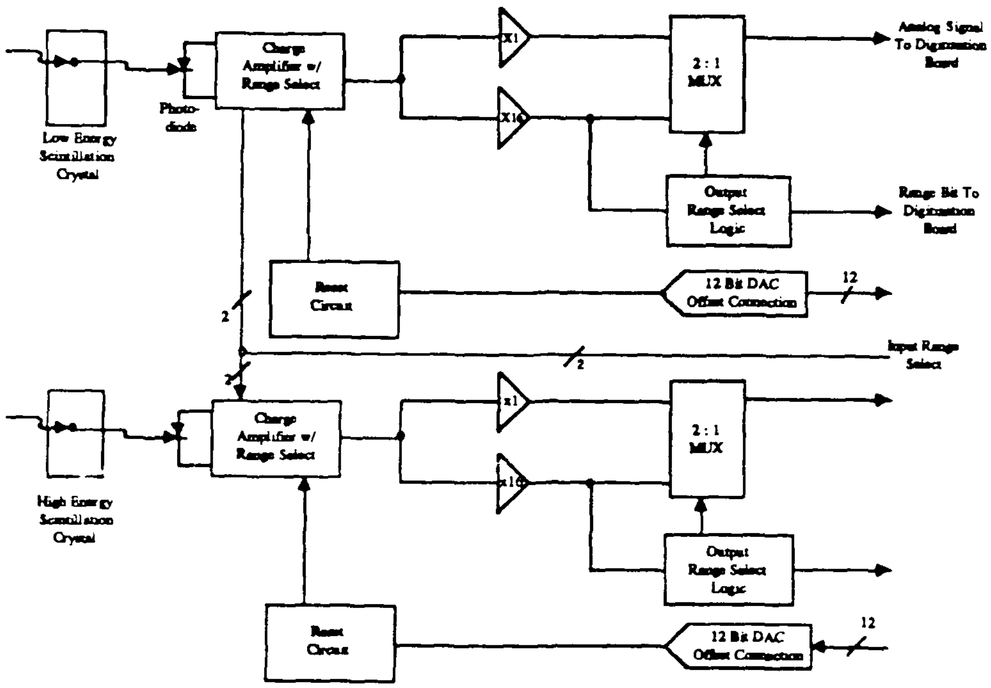

FIGURE 3: Analog Processing Board Data Channel Block Diagram

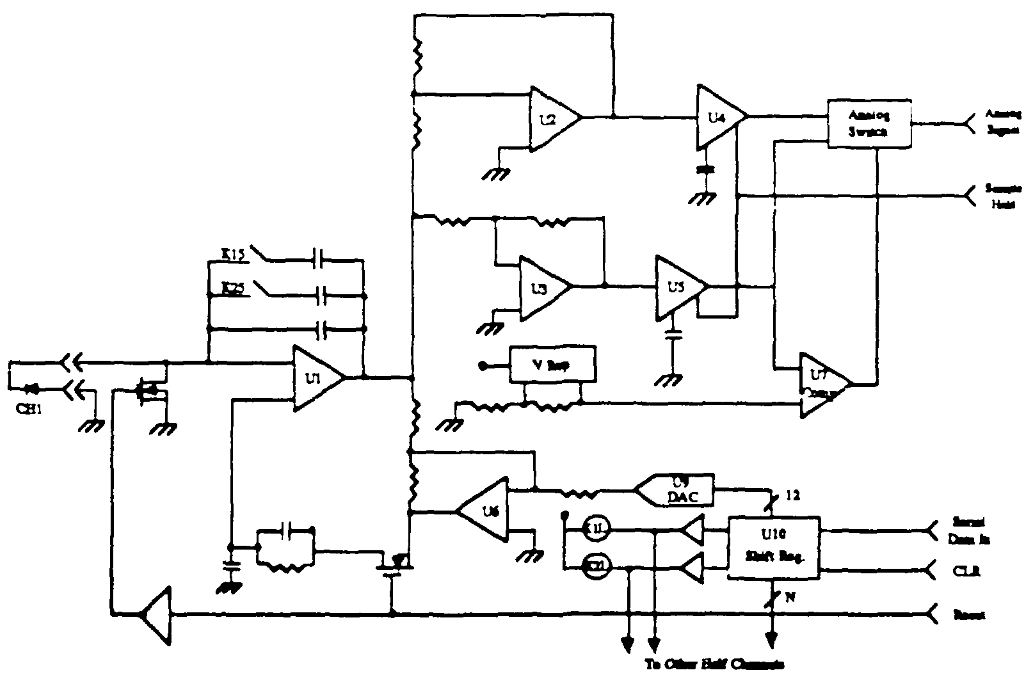

FIGURE 4: Analog Processing Board Half-Channel Circuit

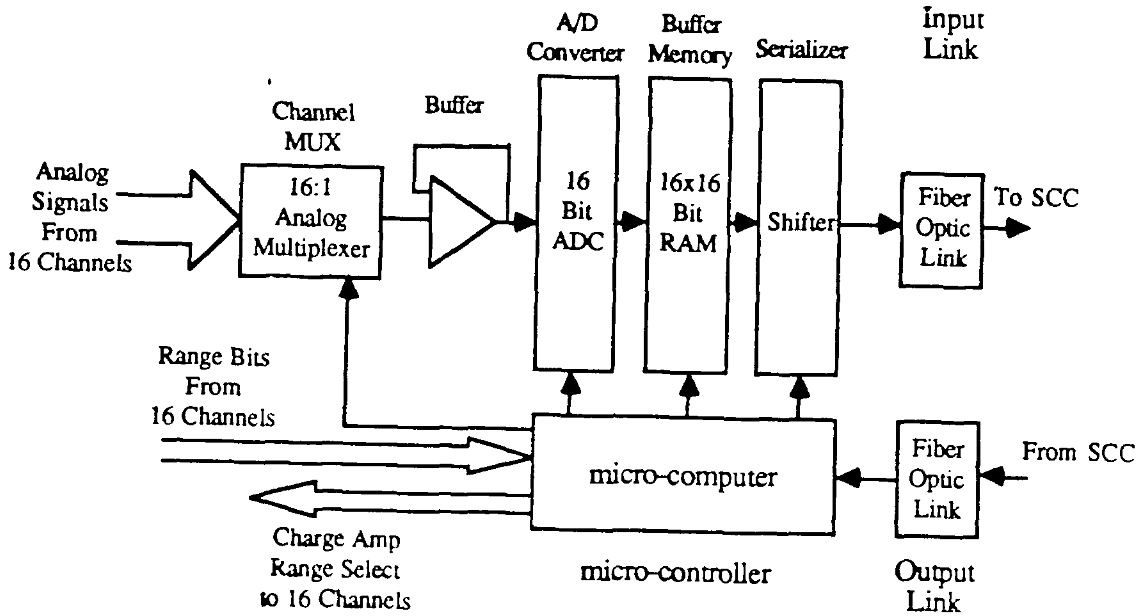

FIGURE 5: Digitization Board Block Diagram

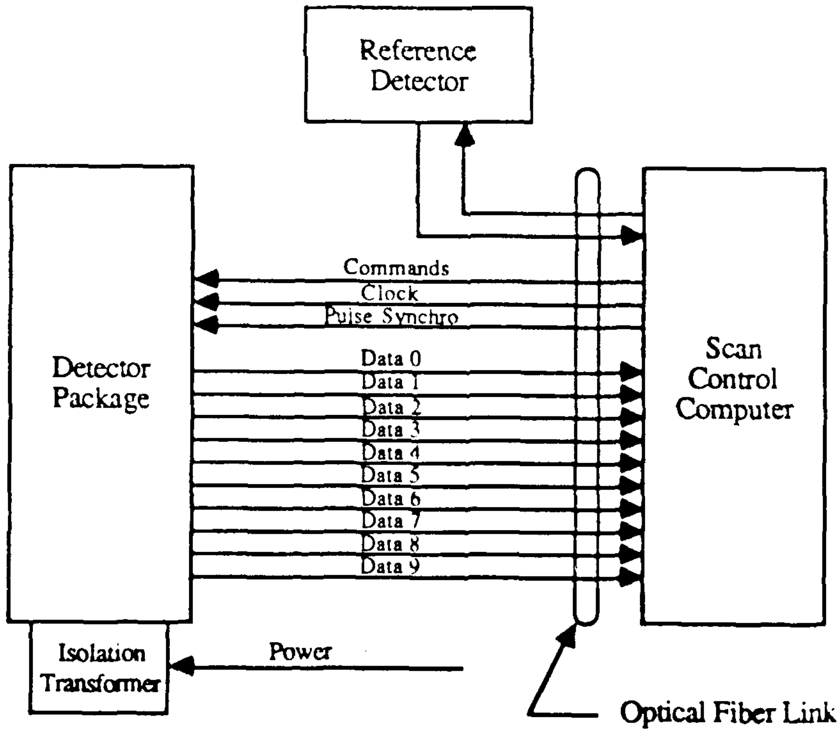

FIGURE 6: Detector Package Cabling

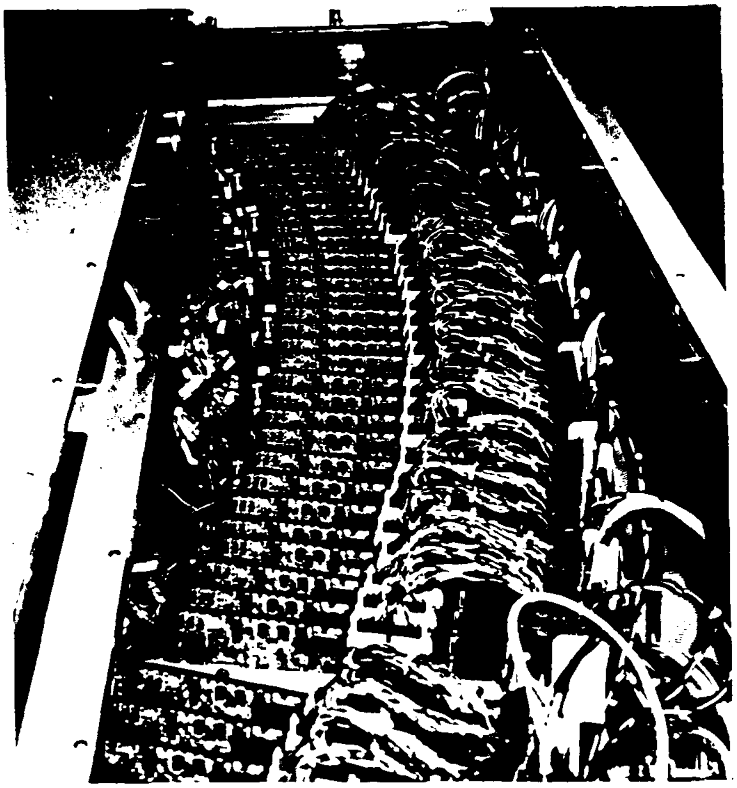

FIGURE 7: Photograph of Data Acquisition Electronics

3.2.1 Dual-Energy Software

The dual-energy software development is divided into four functional modules: data acquisition, dual-energy calibration, image processing, and material cancellation. Many of these software codes already existed before this program and are part of the ARACOR CATS© Software. The goal of this task was to incorporate into CATS© the existing and needed tools to perform dual-energy radiographs and analysis.

The dual-energy technique consists of acquiring and processing the readings from the two arrays of dual in-line detectors. Dual-energy calibration data is obtained by scanning an object of known thickness and composition. Polynomial coefficients can be calculated assuming that the "Compton" and "photoelectric" components of the low-energy and high-energy images of the calibration phantom can be represented as a nth order Chebyshev polynomial. After these coefficients have been determined, the dual-energy data can be separated into two images, namely the "Compton image" and the "photoelectric image," by a simple polynomial evaluation of high- and low-energy

measurements. Component images can be used to cancel a given material and view corrosion, for example, in an aluminum part. A schematic of the dual-energy separation process is shown in Figure 8.

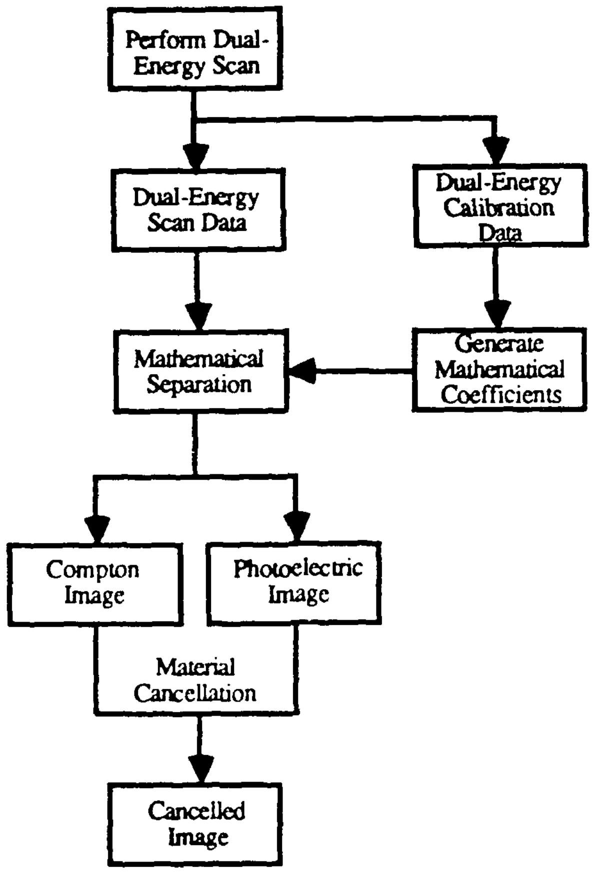

FIGURE 8: Dual-Energy Separation Block Diagram

3.2.2 Laminography Software

The reconstruction algorithm for laminography operates on scan data one raster at a time. Because a given point in the object is not generally visible in all views, the reconstruction problem for laminography is analogous to that of limited-angle fan-beam CT, except that instead of reconstructing the entire cross section of the object at each raster height, only the locus of points lying on the surface of interest need to be reconstructed. The reconstruction process consists of preprocessing the data to obtain better detector-to-detector matching (i.e. flatter images), sorting the data to obtain only the locus of points lying on the surface of interest, convolving the data with a filter function.

and back-projecting a raster at a time onto the locus of the surface associated with that height. A schematic of this laminography algorithm is shown in Figure 9. This algorithm was coded and incorporated into the CATS© software.

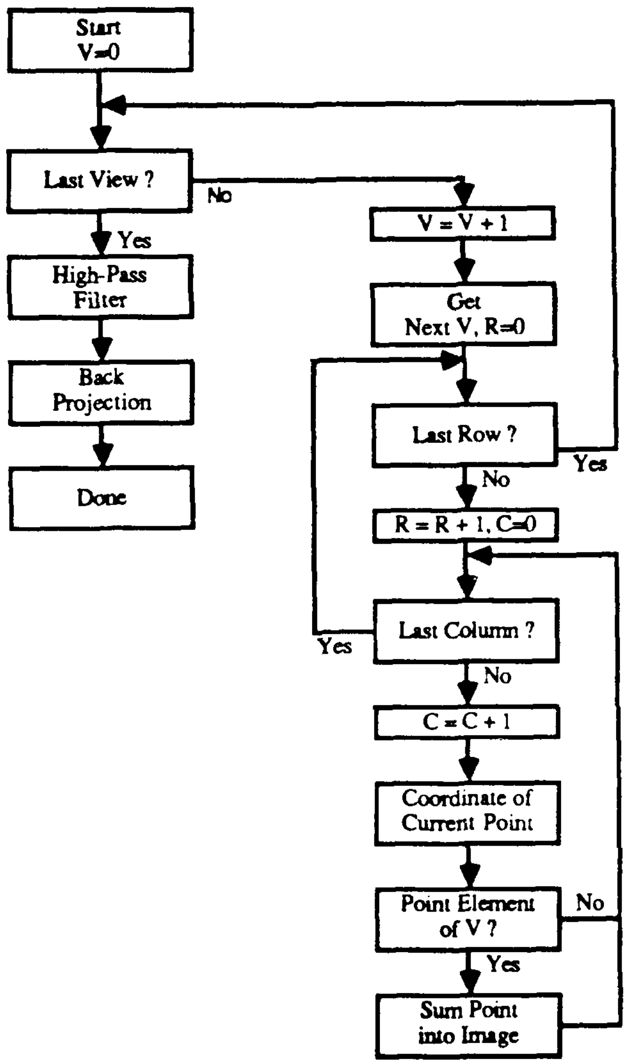

FIGURE 9: Laminography Algorithm Block Diagram

3.2.3 Integration with CATS© Software

CATS© is broken down into four modules. A master program known as MAESTRO allows the user to go back and forth between modules. LEGO is a control program module which allow the operator to set up and perform a scan. The operator can identify the part being scanned, set-up the necessary scan parameters, perform and

monitor the scan all within LEGO. The LEGO commands can be called directly from the MAESTRO Master Menu. RECO is the reconstruction program module which performs data processing and reconstruction of the data acquired in LEGO. VIDEO is a display/analysis program module which allows the operator to view the reconstructed or raw data in various formats. VIDEO utilizes a RAMTEK display monitor for its operation. ARCO is a archiving program module which allows the operator to record the data from scans onto magnetic tape. An outline of these various program modules is shown in Figure 10. Figure 11 shows a photograph of the MAESTRO Master Menu as displayed on the CRT. As mentioned, the LEGO commands can be called directly from this menu. The operator can also call the RECO, VIDEO, or ARCO program modules from this menu. The commands for these three program modules can be called from their respective menus which are shown in Figures 12 through 14.

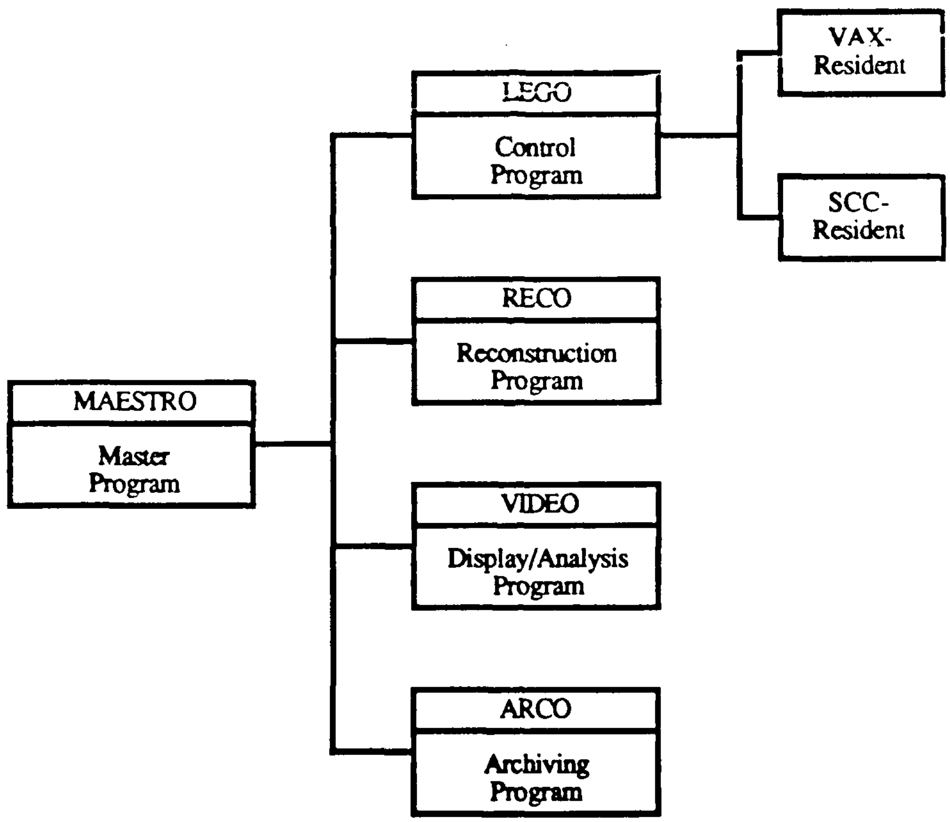

FIGURE 10: Overall CATS© Block Diagram

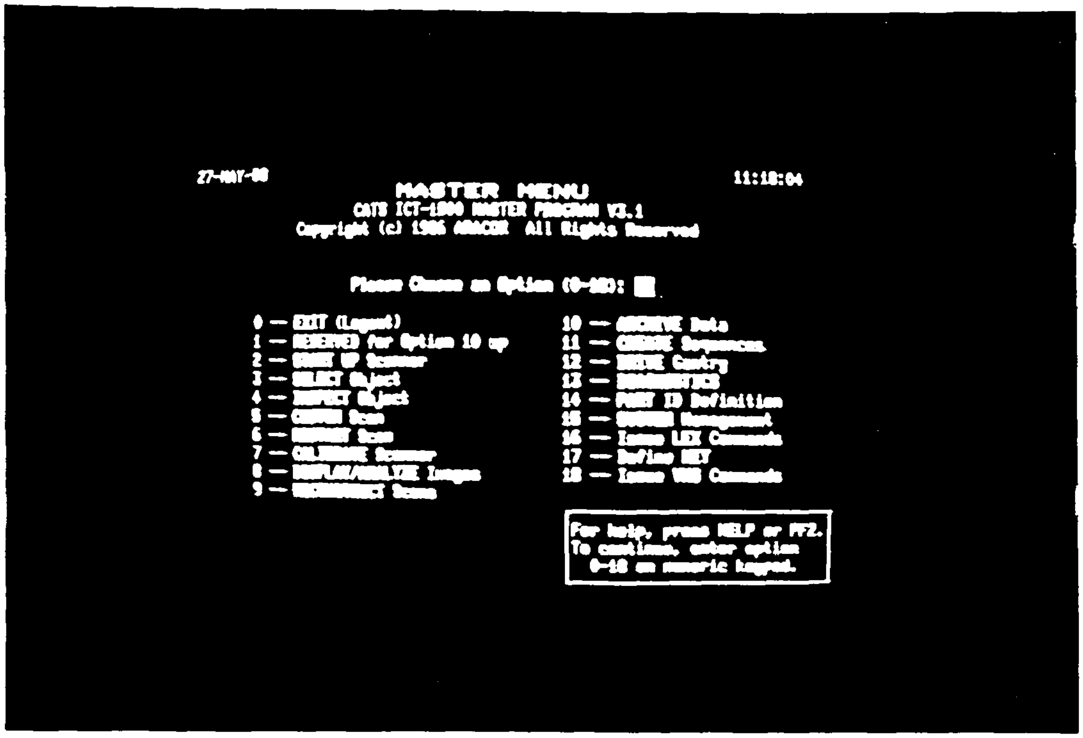

FIGURE 11: MAESTRO Master Menu

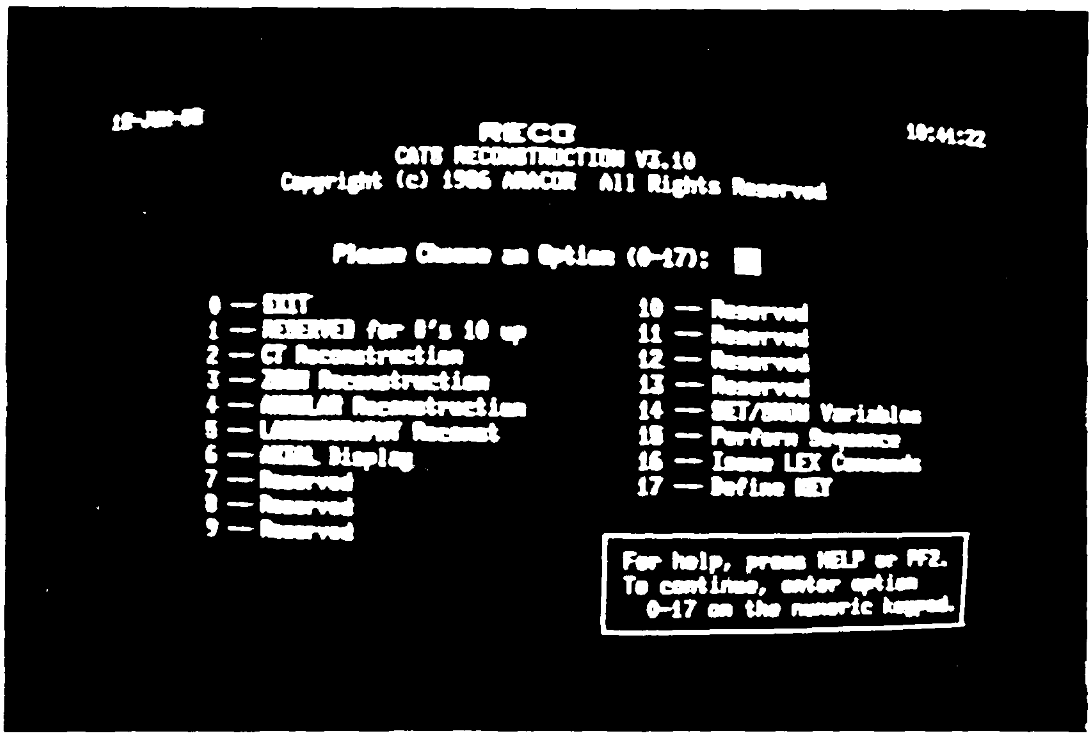

FIGURE 12: RECO Reconstruction Program Menu

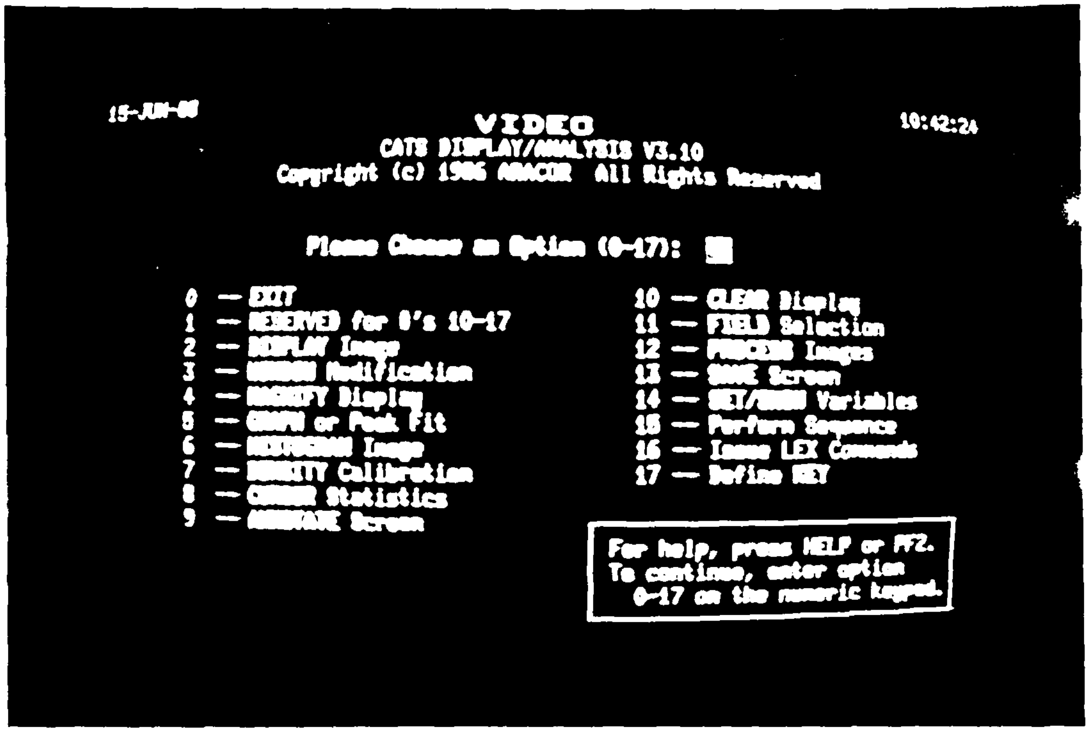

FIGURE 13: VIDEO Display/Analysis Program Menu

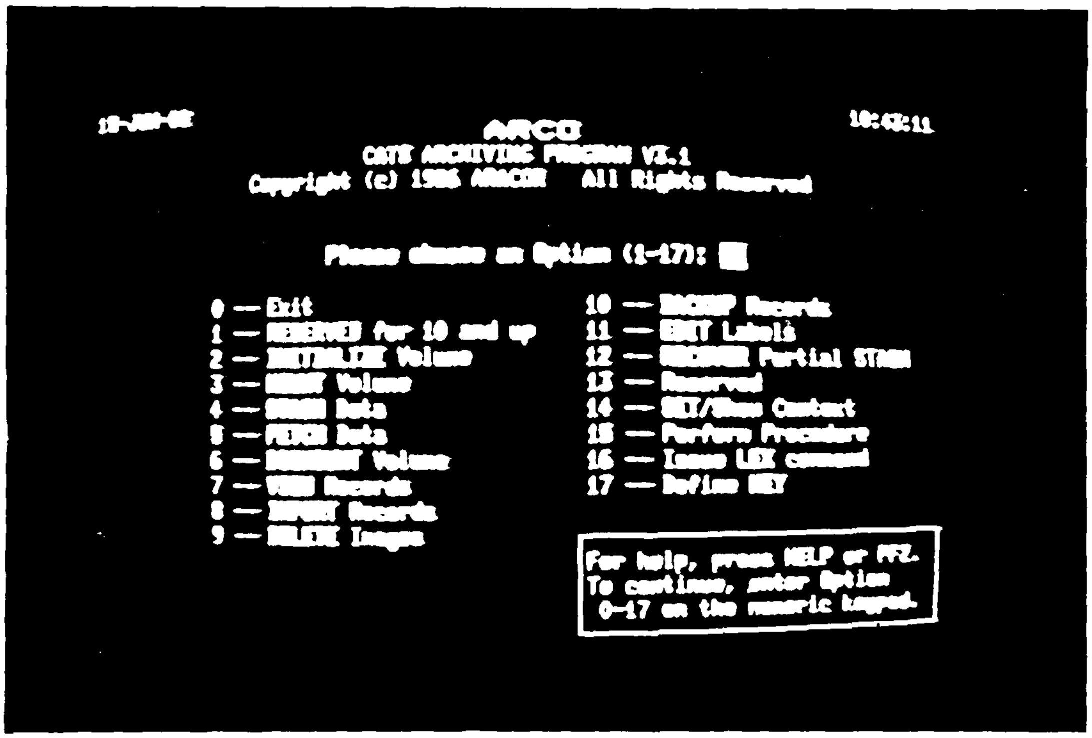

FIGURE 14: ARCO Archiving Program Menu

For a typical scan, the operator would start up the system by turning on the X-ray source and the computer hardware and allowing them to warm up. After positioning the part on the rotary table, the operator would close the door of the radiation facility and proceed to the operator control facility. Upon logging into the CATS© system, the operator would start up the program and define the object to be scanned, define the scan parameters, and begin the scan. To perform a dual-energy radiographic scan, the operator would chose the SCAN Object Option from MAESTRO. This command would bring up the Scan Object menu from which the operator would chose either D.E. CT Scan or D.E. Preview Scan. A photograph of the Scan Object screen is shown in Figure 15 and a photograph of the D.E. CT Scan screen is shown in Figure 16. Once choosing the D.E. CT or Preview Scan option, the operator would fill in the necessary parameters on the screen and begin the scan. To perform a laminography scan, the operator would simply choose LAMIONOGRAPHY Scan from the Scan Object Menu and fill in the necessary parameters to begin the scan. A photograph of the Laminography Scan screen is shown in Figure 17. After the scan is completed, the scan data would need to be reconstructed or processed using RECO. The reconstructed or processed data could then be displayed, analyzed, and archived as desired. The operational overview of the LAM/DE CATS© software package is shown in Figure 18.

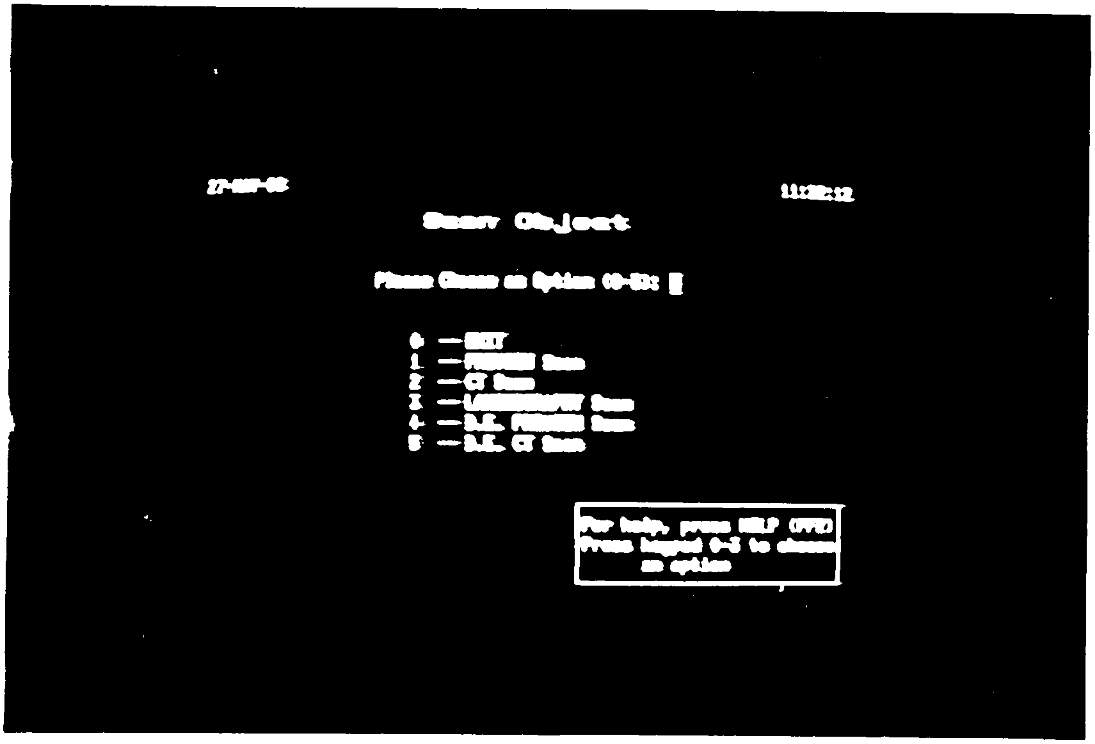

FIGURE 15: Scan Object Menu

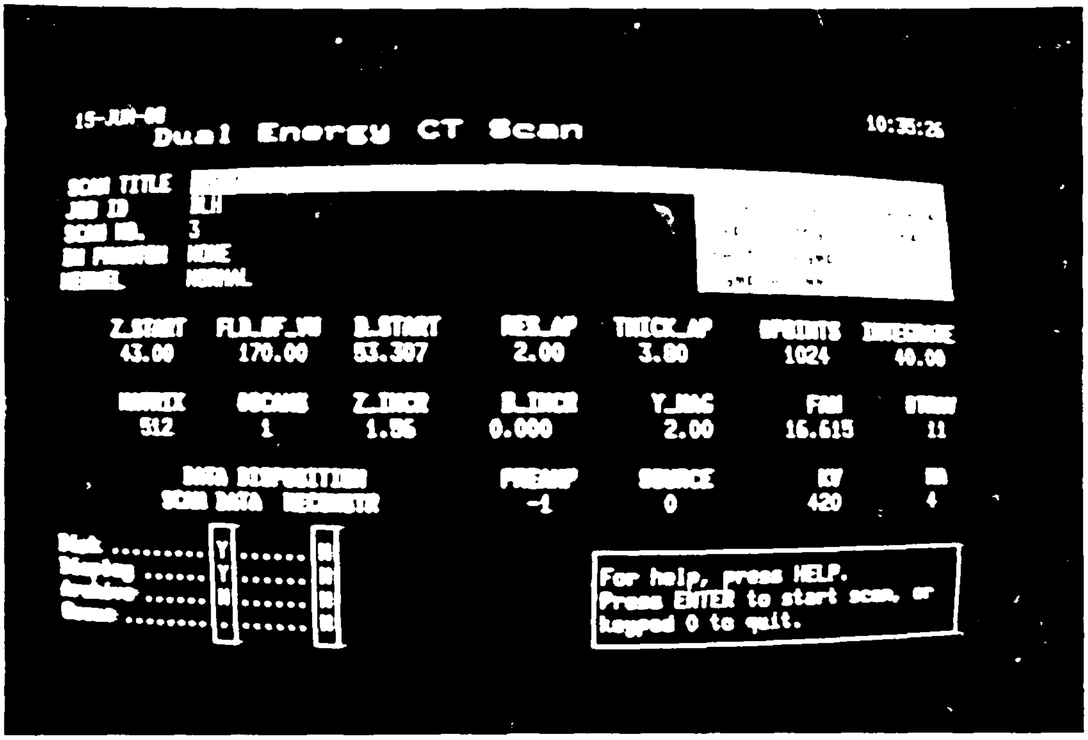

FIGURE 16: Dual-Energy CT Scan Screen

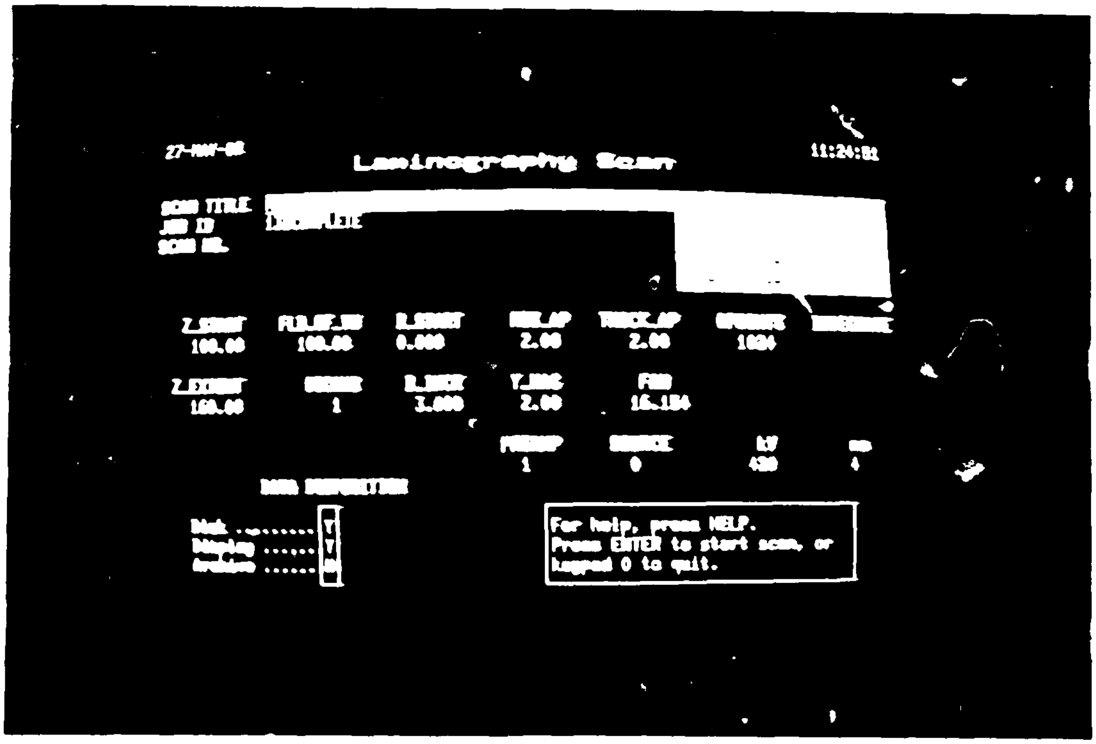

FIGURE 17: Laminography Scan Screen

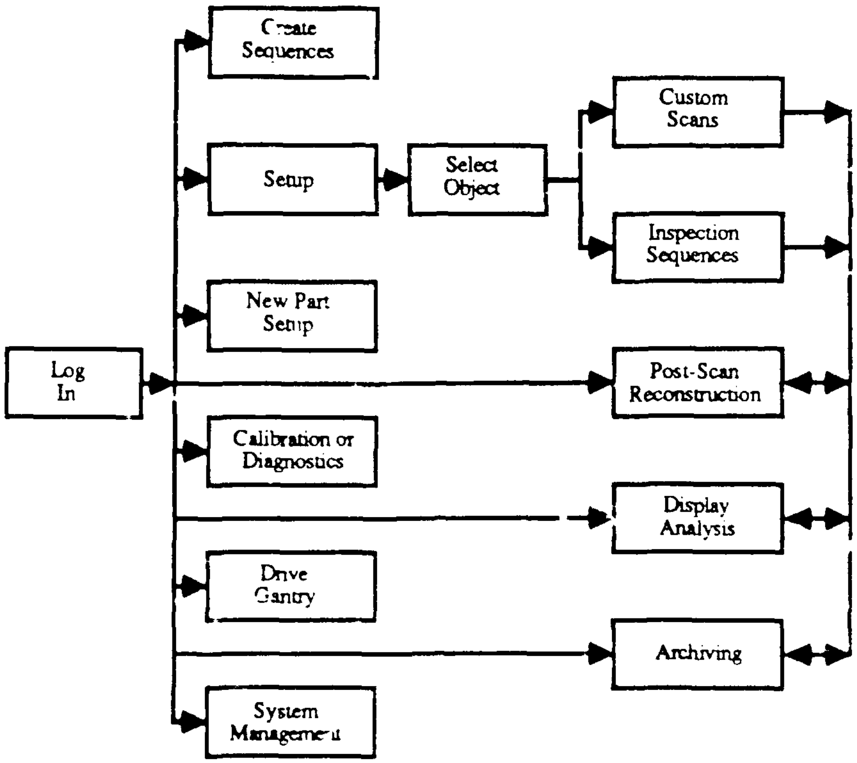

FIGURE 18: Operational Overview of CATS© Software

CATS© can not only be driven by menus, which are most convenient for most applications, but can also be driven by LEX commands. LEX commands are a powerful underlying command language that can be used to set up automatic sequences to meet the needs of a particular scanning program. This is very useful if several reconstructions or archives need to be done on a series of scans. LEX commands eliminate the need for the operator to reconstruct or archive each file individually. CATS© is also equipped with a HELP function and a function key definition capability.

3.2.4 Control Software

Three libraries were created to incorporate control of the LAM/DE system into the CATS© software package. The first library is named HSLIB and it allows the operator to control the handling system from the operator control terminal. The computer is able to talk to the handling system but the handling system cannot talk back to the computer. As a result, the control library written for the handling system is able to give commands

to the handling system to tell it where to go but there is no way for the computer to know where the handling system is while it is moving. In most cases, however, this does not create a problem. This inconvenience could be eliminated with additional development. The second library is named SRCLIB and it controls operation of the X-ray source. The third library is named DETLIB and it controls operation of the detector package. This includes operation of the slice thickness and resolution collimators along with the data acquisition electronic settings. These libraries along with the software coding for dual-energy and laminography were incorporated into the VAX 11/750 system utilizing the scan control computer and the array processor.

3.3 SYSTEM INTEGRATION AND EVALUATION

An overview of the system integration and evaluation tasks are reviewed below. System integration was completed but system evaluation could not be completed within the program funding limits.

3.3.1 System Integration

The LAM/DE system has been fully integrated. After the design phase was completed, the various components were procured and manufactured. The components were assembled and the software development was incorporated into the CATS© software to achieve a fully operational laminography/dual-energy system.

A photograph of the entire LAM/DE scan system is shown in Figure 19 that shows the X-ray source on the right, the handling system in the middle, and the detector package on the left. The handling system is situated in a pit as described elsewhere.

3.3.2 System Evaluation

A test plan was drafted and revised. The test plan document outlined the design of various phantoms to evaluate DE performance of the LAM/DE system and describes the various tasks associated with the phantoms to characterize the LAM/DE unit. Funds were not sufficient, however, to fabricate these phantoms or implement the Test Plan.

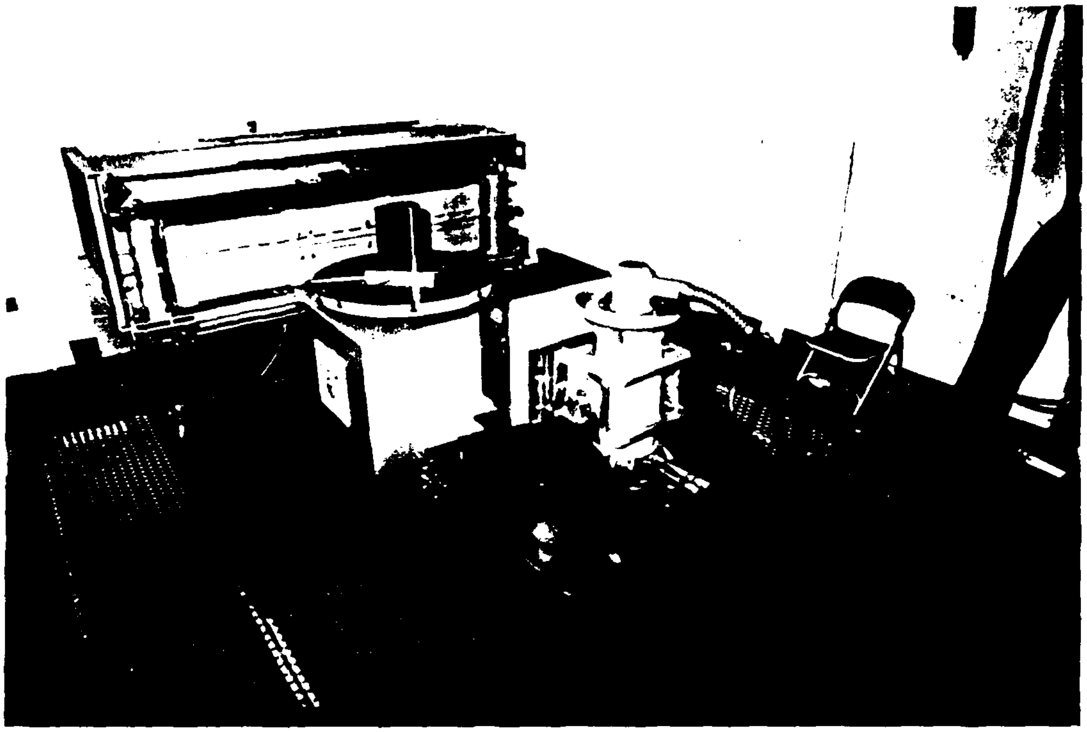

FIGURE 19: Photograph of Fully Integrated LAM/DE System

3.4 SYSTEM DEMONSTRATION

A demonstration of the LAM/DE system to a joint government/industry audience was not performed due to insufficient funds.

SECTION 4

CONCLUSIONS AND RECOMMENDATIONS

This program has developed a fully integrated, fully operational inspection system capable of laminography and dual-energy measurements. This system provides a powerful NDE tool for use in countless military/industrial applications. The limits of performance have not been fully evaluated, however, and it is recommended that further funding be used to completely evaluate and characterize the capabilities of this unique system. The wealth of knowledge to be gained from such an endeavor can only further advance the rapidly changing field of NDE imaging.

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